THE EFFECTS OF ANESTHESIA AND CARDIAC BYPASS ON PULMONARY COMPLIANCE IN MAN*

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PULMONARY compliance has been shown to be decreased for a period of several weeks following anesthesia and open-heart operations.[1,2] This postoperative decrease in compliance is a further change from the low preoperative values seen in patients with heart disease and pulmonary hypertension.[3,4] The prolonged postoperative decrease in pulmonary compliance has not been correlated with changes in lung volumes or in pulmonary gas exchange. The purpose of this study is to relate changes in compliance to other pulmonary functions in the post-cardiotomy patient an an attempt to simplify the study of pulmonary function in patients who undergo operations on the heart.

METHODS

Patients with mitral stenosis were studied before and after cardiac bypass. The subjects were studied in the supine position on four occasions: preoperatively, 1 to 2 days prior to operation; in the recovery room immediately after operation while breathing continued spon-

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GLOSSARY

C_L	lung compliance in ml/cm H_2O
W_T	total work of breathing in gram-cm/ml
Wel	elastic work of breathing in gram-cm/ml
Wres	resistive work of breathing in gram-cm/ml
VC	vital capacity
FRC	functional residual capacity
RV	residual volume
TLC	total lung capacity
$FEV_{1.0}$	forced expiratory volume in one second
FVC	forced vital capacity
V_D/V_T	dead space-tidal volume ratio
P_{aO_2}	arterial oxygen tension in mm Hg
$(A-a)\ D_{O_2}$	alveolar-arterial oxygen tension difference in mm Hg
$\dot{Q}_{V_A}/\dot{Q}_T$	venous admixture in per cent (breathing air)
$\dot{Q}_S/\dot{Q}_T$	right to left shunt on 100% O_2
%	per cent of predicted value
Shunt component	shunt portion of the $(A-a)D_{O_2}$ (breathing air)
Nonshunt component	nonshunt portion of the $(A-a)\ D_{O_2}$ (breathing air)

taneously; and approximately 1 week (6 to 10 days) and 3 weeks (14 to 21 days) after operation. Anesthesia was maintained with halothane and oxygen before, during, and after the bypass procedure. Pulmonary compliance was measured by means of a water-filled esophageal catheter placed in the lower esophagus and a Statham PR-23-2D-300 manometer, calibrated with a water manometer.[5, 6, 7] A Fleisch pneumotachograph, dead space 15 ml. linear over the flow rates used, heated with an external voltage source to prevent condensation of water was used with a Starham PM 5-0.2-300 manometer measuring the differential pressure across the penumotachograph. Volume (V) was determined by electronic integration of the flow signal. Calibration was made with a 1-liter super syringe. A photographic X-Y recorder was used for the pressure-volume loop. Dynamic pulmonary compliance, the ratio of tidal volume to change in pressure between the points of zero flow at the extremes of the tidal volume, is expressed in ml.BPTS/cm.H_2O. Per cent predicted pulmonary compliance was derived for each patient based on the relation to compliance as developed by Frank and his co-workers.[8] The areas in the pressure-volume record representing elastic work (W_{el}) and flow-resistive work (W_{res}) were measured with a self-compensating polar planimeter, and are expressed in gram-cm./ ml.BTPS. All measurements of the mechanics of breathing were made with subjects supine and breathing spontaneously. Lung volumes are reported at BTPS. Vital capacity (VC) and forced expiratory volume in one second ($FEV_{1.0}$) were measured with a Collins 13.5-l spirometer. Functional residual capacity (FRC) was measured with an open circuit technique while the patient breathed oxygen for seven minutes.[9] Nitrogen was measured with a nitrogen analyzer (Model 305AR, Med-Science). The per cent of predicted values for lung volumes are based on the relation: $\frac{\text{measured value}}{\text{predicted value}} \times 100 = \%$ predicted value. The predicted values are based on a compilation of currently available norms.[10] Arterial blood samples were collected through an indwelling teflon catheter and were iced immediately. Arterial oxygen (P_aO_2) and carbon dioxide (P_aCO_2) tensions and pH were measured with modified Clark O_2 electrode,[11] a modified Severinghaus CO_2 electrode,[12] and a modified capillary glass electrode respectively in a water bath at 37°C. The O_2 electrode was calibrated with blood of known PO_2 obtained by tonometry at 37°C. using 5 ml. of the original arterial sample.[13]

Alveolar oxygen tension (P_AO_2) is derived from the following reactions:

$$\text{(breathing air) } P_AO_2 = P_IO_2 + \frac{P_ACO_2 \times F_IO_2 \times (1\text{-}R)}{R} - \frac{P_ACO_2}{R}$$

$$\text{(breathing 100\% oxygen) } P_AO_2 = P_IO_2 - P_ACO_2 - P_AN_2$$

where P_ACO_2 was assumed equal to P_aCO_2. Alveolar nitrogen tension (P_AN_2) was measured with the nitrogen analyzer. Respiratory quotient (R) was determined from measurements of the O_2 consumption (VO_2) and CO_2 production (VCO_2).

TABLE I. CHARACTERISTICS OF PATIENTS

Subject No.	Age	Sex	BSA M^2	Cardiac catheterization: PA mm. Hg.	Mean PA mm. Hg.	Wedge mm. Hg.	C.I. l/min./m.²	Diagnosis
1	54	M	1.9	50/19	43	18	2.1	MS & MI
2	17	M	1.7	88/38	53	40	1.5	MS & MI
3	49	M	1.9	102/46	72	33	1.9	MS
4	53	F	1.48	70/15	—	13	—	MS
5	36	F	1.56	41/17	29	16	—	MS & AS & AI
6	57	M	1.98	52/30	36	24	—	MS
7	70	M	1.86	73/21	44	31	1.8	MS & MI
8	64	F	1.31	—	—	—	—	MS
9	51	M	1.76	—	—	—	—	MS
10	50	F	1.64	—	—	—	—	MS & MI
11	58	F	1.48	—	—	—	—	MS
12	50	F	1.48	—	—	—	—	MS

M=mitral; A=aortic; S=stenosis; I=insufficiency.

The shunt and nonshunt components of the (A-a) D_{O_2} breathing air were calculated using the value of Q_S/Q_T obtained during oxygen breathing.[14]

$$\text{Venous admixture } (Q_{VA}/Q_T) = \frac{C_c'O_2 - C_aO_2}{C_c'O_2 - C_{\bar{v}}O_2}$$

where $C_c'O_2$ C_aO_2 and $C_{\bar{v}}O_2$ are oxygen contents in end capillary, arterial, and mixed venous blood samples, respectively. $C_c'O_2$ was estimated from $P_c'O_2$ which is assumed to equal alveolar arterial tension (P_{AO_2}). Also assumed was an arteriovenous oxygen content difference of 5 volumes per cent.[15] Q_S/Q_T, the fraction of cardiac output that passed through right to left shunts during 100% oxygen breathing, is based on the same relation as the venous admixture equation.

RESULTS

Characteristics of the 12 patients studied are listed in Table I. All were patients with mitral stenosis. In the 7 patients who underwent cardiac catheterization the pressures in the pulmonary artery varied from 102/46 to 41/17. The preoperative lung function studies included determinations of pulmonary mechanics, lung volumes, and arterial blood gases.

In Table II are the values of mechanics of breathing studied preoperatively. Pulmonary compliance is reduced to 52% of the predicted value preoperatively.

TABLE II. PREOPERATIVE PULMONARY MECHANICS*

	Mean	± SE
C_L (ml.BTPS/cm. H_2O)	76.3	9.2
C_L (per cent)	51.6	6.4
W_T (gram-cm./ml.)	6.3	0.8
Wel (gram-cm./ml.)	3.4	0.3
Wres (gram-cm./ml.)	2.9	0.6

*Eleven patients.

TABLE III. PREOPERATIVE PULMONARY VOLUME*

	Measured values		Per cent predicted values	
	Mean	± SE	Mean	± SE
VC (L_{BTPS})	2.5	0.2	72.8	6.3
FRC (L_{BTPS})	2.4	0.2	78.7	7.4
TLC (L_{BTPS})	4.4	0.3	79.8	4.8
RV/TLC (%)	44.8	3.8	129.8	8.9
$FEV_{1.0}$ (L_{BTPS})	1.7	0.2	61.5	5.3
$FEV_{1.0}$/FVC (%)	75.6	2.9	97	3.7
RV (L_{BTPS})	1.9	0.2	105.4	10.2

*Twelve patients.

TABLE IV. PREOPERATIVE ARTERIAL BLOOD GASES*

	Breathing air	
	Mean	± SE
Pa_{O_2} (mm. Hg)	77.8	4.6
(A-a) D_{O_2} (mm. Hg)		
Total	32.6	3.2
Shunt	12.6	2.7
Nonshunt	20.0	4.3
$Q_{VA}/Q_T \times 100$ (%)	10.3	1.7
$V_D/V_T \times 100$ (%)	42.2	2.4
	Breathing 100% O_2	
	Mean	± SE
Pa_{O_2} (mm. Hg)	589.9	15.6
(A-a) D_{O_2} (mm. Hg)	81.8	14.3
$Q_S/Q_T \times 100$ (%)	4.7	0.8

*Eleven patients.

TABLE V. POSTOPERATIVE STUDIES OF PULMONARY FUNCTION

	Preoperative			*Postoperative* *Intermediate*			*6 to 10 Days*			*14 to 21 Days*		
	Mean	*± SE*	*n*	*Mean*	*± SE*	*n*	*Mean*	*± SE*	*n*	*Mean*	*± SE*	*n*
CL (ml.BTPS/cm. H_2O)	76.3	9.2	11	***40.1	7.8	6	64.8	11.2	5	76.3	13.7	6
CL % (per cent)	51.6	6.4	11	***26	3.6	6	44.4	5.4	5	49.9	6.6	6
WT (gram-cm./ml.)	6.3	0.8	11	*8.5	0.5	5	8	0.7	5	6	0.9	5
Wel (gram-cm./ml.)	3.4	0.3	11	3.8	0.7	5	4	0.5	5	3.9	0.5	5
Wres (gram-cm./ml.)	2.9	0.6	11	4.7	1.0	5	4	0.7	5	2.1	0.7	5
Pa_{O_2} (AIR) (mm. Hg)	77.8	4.6	11	*55.9	3.3	6	N. D.		–	70.8	4.8	6
Pa_{O_2} (100% O_2) (mm. Hg)	589.9	15.6	11	**389	65.9	6	N. D.		–	572.6	19.2	6
VC (LBTPS)	2.5	0.2	12	N. D.		–	N. D.		–	***1.8	0.4	5
VC% (per cent)	72.8	6.8	12	N. D.		–	N. D.		–	***54	4.9	5

N.D.—not done.
Paired comparison.[16] Significant differences from preoperative values are noted as follows:
*$P < 0.05$.
**$P < 0.02$.
***$P < 0.01$.

Preoperative lung volumes listed in Table III show the following to be reduced: vital capacity (VC), functional residual capacity (FRC), total lung capacity (TLC), and forced expiratory volume in one second ($FEV_{1.0}$). The ratio of residual volume/total lung capacity (RV/TLC) is increased while the residual volume (RV) and $FEV_{1.0}$/FVC ratio are within normal limits.

Listed in Table IV are the preoperative values for arterial blood gases. The values of P_aO_2 while the patient breathed air or 100% O_2 are reduced; while (A-a) D_{O_2}, venous admixture (Q_{VA}/Q_T), Q_S/Q_T, dead space/tidal volume ratio (V_D/V_T) are increased from expected values.

In Table V and Figure 1 are the mean values (±SE) of pulmonary compliance, per cent predicted pulmonary compliance, total work of breathing, and elastic and resistive components of the work of breathing P_aO_2 while the patient breathed air and 100% O_2, vital capacity, and per cent predicted vital capacity at each of the four periods of measurement. In the immediate postoperative period the functions to show a significant difference ($P<0.05$) from the preoperative values were pulmonary compliance ($P<0.01$), total work ($P<0.05$) and P_aO_2 breathing air ($P<0.05$) and 100% O_2 ($P<0.02$). Total work of breathing was still significantly elevated ($P<0.05$) at 6 to 10 days postoperatively. The only measurement that still showed a significant change at 14 to 21

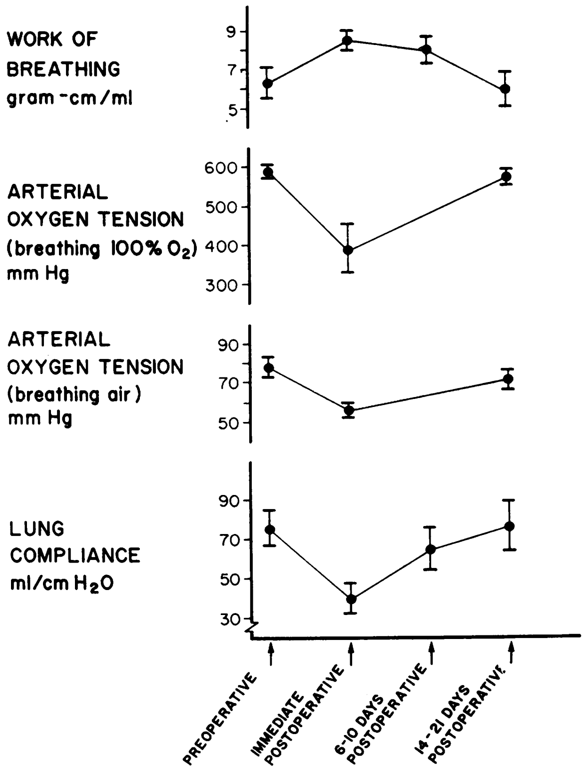

Fig. 1. Work of breathing, arterial oxygen tension breathing air and oxygen, and pulmonary compliance before and after cardiac bypass.

days into the postoperative period was vital capacity and per cent predicted vital capacity ($P<0.01$).

Data from all four study periods were used for correlation analysis. In Figure 2 are plotted the values of lung compliance versus per cent of predicted vital capacity, where the correlation coefficient (r) = 0.622 ($P<0.02$). In Figure 3 is the plot of P_{aO_2} breathing air versus pulmonary compliance where $r = 0.558$ ($P<0.02$). P_{aO_2} on 100% O_2 had a correlation coefficient of 0.453 ($P<0.05$) when plotted versus pulmonary compliance. Per cent predicted vital capacity had the same degree of correlation with P_{aO_2} breathing air ($r = 0.785$; $P<0.001$) and 100% O_2 ($r = 0.748$; $P<0.005$) as pulmonary compliance. Figure 4 represents the correlation of the residual volume/total lung capacity ratio to pulmonary compliance where $r = -0.603$ ($P<0.02$); a similar degree of association was present when RV/TLC was plotted against per cent predicted vital capacity.

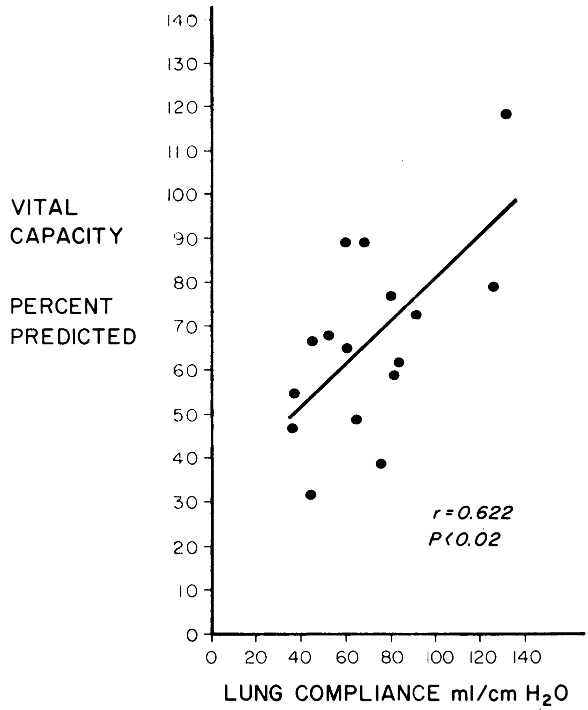

Fig. 2. Plot of vital capacity, per cent of predicted value, versus pulmonary compliance.

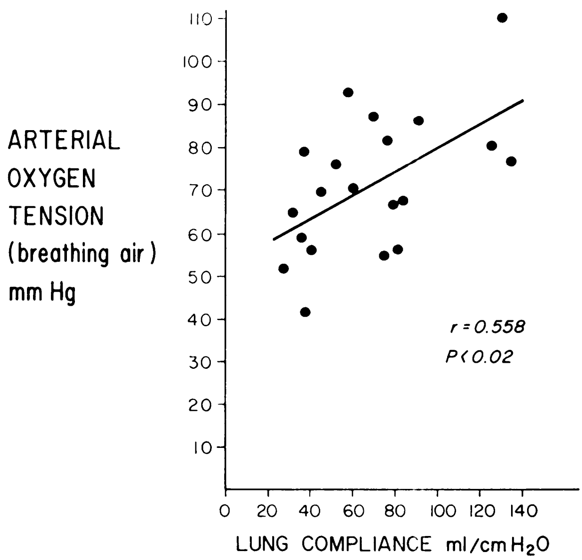

Fig. 3. Plot of arterial oxygen tension while patient is breathing air versus lung compliance.

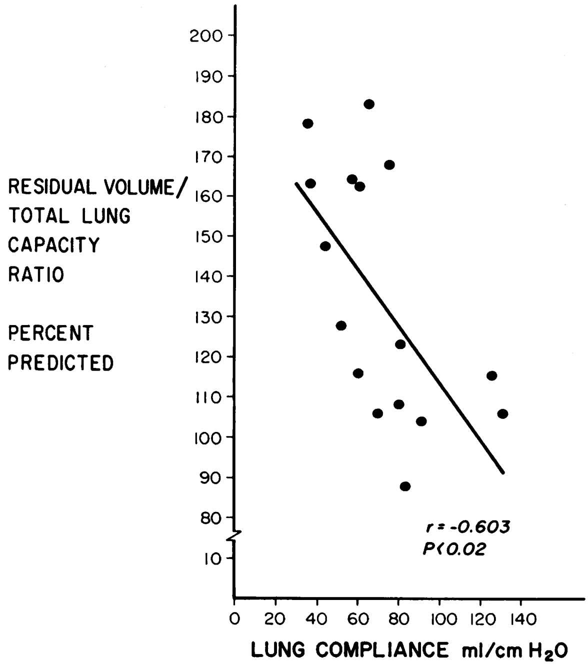

Fig. 4. Plot of residual volume/total lung capacity ratio versus pulmonary compliance.

Discussion

The pathophysiology of the lung in mitral stenosis has been studied by Parker and Weiss,[17] who attempted to correlate structural changes in the lung with physiologic disturbance. These investigators found thickened alveoli exhibiting increased amounts of collagen and considered that this structural alteration contributed to the "stiffness" of the lungs. However, they were not able to correlate the anatomical changes with disturbed lung function.

The compliance data in Table V and Figure 1 are in agreement with data of previous investigators.[1,2] The preoperative values are less than normal and a further decrease of approximately 50% was noted immediately postoperatively. Compliance returns toward preoperative values over a three-week postoperative period.

Compliance, as a measure of the stiffness of the lung, has been correlated with other aspects of lung function. Vital capacity has been found to correlate well with pulmonary compliance in a number of studies in which different techniques were used.[4,5,18-20] This correlation was observed in the present study ($r = 0.585$, $P<0.02$). When per cent predicted vital capacity was correlated with pulmonary compliance (Figure 2) this association was also of a high degree ($r = 0.622$, $P<0.02$).

In some instances the location of the esophageal catheter has been found to influence the measured value of pulmonary compliance. Mead and Whittenberger[21] demonstrated a marked variation with differing lengths of esophageal catheters whereas other workers[4, 5] have concluded that the location of the catheter was not critical. The present studies were performed with the catheter tip located in the lower third of the esophagus.

In some studies functional residual capacity has been found to have a high degree of correlation with compliance,[7, 18, 22] whereas in others no correlation was found.[4, 20] In the present study we found a poor and statistically insignificant correlation between functional residual capacity and pulmonary compliance.

Frank et al.[4] and Cherniack and Brown[20] found a significant correlation between TLC and pulmonary compliance. We did not demonstrate this, but found RV/TLC per cent of predicted to have a high degree of association with compliance ($r = -0.603$, $P<0.02$). See Figure 4.

The values of work of breathing plotted in Figure 1 are in agreement with previous studies, which demonstrated the marked increase in the work of breathing immediately after operation on the heart and a return toward preoperative control values over several postoperative weeks.[1, 23, 24]

There seem to have been no previous attempts to correlate arterial oxygen tension with compliance. As shown in Figure 3, the value of P_{aO_2} while the patient breathed air has a high degree of association with pulmonary compliance. This magnitude of association is also present for the (A-a) D_{O_2} and venous admixture when breathing air, and for the P_{aO_2}, (A-a) D_{O_2}, and Q_S/Q_T when he is breathing 100% O_2.

Vital capacity measured at the 14- to 21-day postoperative period was the single measurement which remained significantly different from the preoperative value. Compliance is one of numerous factors that influence the measurement of vital capacity.[25] Measurements of lung volumes in the preoperative period (Table III) show a pattern consistent with restrictive pulmonary disease but not of obstructive pulmonary disease. Values for arterial blood gases at 14 to 21 days are not significantly different from the preoperative values; therefore it is likely that there has been no loss in lung tissue available for gas exchange. It is most improbable that neuromuscular or respiratory center depression persists this late in the postoperative period. The most reasonable explanation for the failure of vital capacity to return to preoperative values as other functions studied had done at 14 to 21 days is limitation of thoracic expansion secondary to the surgical incision. As a single test, vital capacity appears to yield reliable information about over-all pulmonary function in patients undergoing operation for the relief of mitral stenosis.

Summary

Measurement of pulmonary function before and after cardiac bypass in 12 patients with mitral stenosis was undertaken in an attempt to simplify the study of pulmonary function in these patients. Correlations between pulmonary compliance and vital capacity, arterial oxygen tension, and residual volume/total lung capacity ratio are of such a degree that measurement of vital capacity has a 95% or better probability of reflecting the disturbed lung function present in these patients. As a single measurement, vital capacity provides reliable information regarding over-all lung function in the surgical patient who is suffering from acquired valvular heart disease.

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